Electronic Contact Lens for Senses beyond Sight

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Abstract

Most advances in electronic contact lenses are aimed at active vision enhancement. Here, additional sensing and display functionalities are discussed. Integration of individually addressable microelectrodes (30 µm diameter) is demonstrated for biomarker detection in tear fluid, with a focus on future applications, challenges, and integration with display technology.

Author Keywords

Smart contact lenses; Electrochemistry; Non-invasive sensing; Flexible electronics; Wearable sensors

1. Objectives and Background

While the field of Smart Contact Lenses (SCLs) has started to establish itself, with mature support technologies in wireless communication and power [1], [2], fabrication techniques [3], [4] and sufficient biocompatibility to yield a clinically approved device [5], the opportunities for sensor integration and multimodal use have only just begun to be explored [6], [7], [8]. A range of new technologies is currently undergoing development. Integration of Liquid Crystal Display (LCD) [9], [10] leads to the possibility of active vision correction or enhancement, with electronic focusing and other techniques. SCLs with a single pixel LED indicator have also been reported [7], [6]. Medical data may be obtained by embedding sensors in a SCL, working in a continuous or intermittent mode throughout the day. For example, the Sensimed Triggerfish [11] uses a simple embedded strain gauge to measure Intra-Ocular Pressure (IOP) for a 24 hour period. This data captures the entire diurnal cycle of IOP, which gives clinicians more beneficial information than the single daily measurement usually performed during glaucoma treatment.

Continuous, unobtrusive sensing may be particularly beneficial in a number of other medical scenarios. Electrochemical sensors have previously been embedded in SCLs with the objective of measuring glucose [1], [6] and lactate [12], while many other biomarkers have proposed for sensing in the lachrymal fluid, including alcohol, hormones such as cortisol, serotonin and dopamine [13]. Many of these quantities vary throughout the day, and often a diagnosis or clinical conclusion relies on time-series trends of the biomarkers, rather than a single measurement. When investigating a disrupted cortisol response, for example, the profile over the course of several hours is of interest [14]. In the absence of continuous measurement, clinicians may be unable to draw accurate conclusions, and without unobtrusive sensing, the conditions of the measurement may be disrupted (particularly in the case of stress-correlated biomarkers such as cortisol).

Work towards active drug delivery systems integrated into SCLs has also been reported [8]. These individual functionalities – including displays, sensors and drug delivery systems – are usually designed separately, but the ultimate goal of a medical SCL may include a number of these functions integrated within a single device. For example, a drug delivery system may be triggered – and dose and timing calculated – with reference to measurements taken by a suite of electrochemical (or other) sensors, and a display may provide indication to the user of this process. To achieve this ultimate goal, it is essential that our measurements are robust, accurate and reliable, and that we work towards devices which share compatible fabrication methods, designs and system architectures.

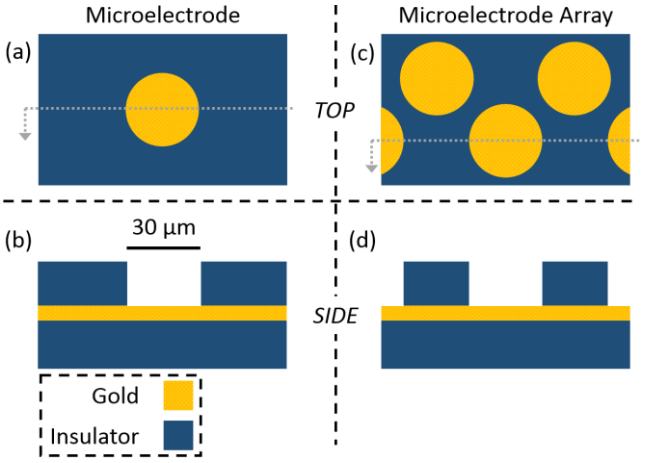

Figure 1. Illustrations: (a) Top view of a 30 µm diameter microdisc electrode; (b) Side view of microelectrode; (c) Top view of an array of microdisc electrodes; (d) Side view of array of microelectrodes.

Previously reported electrochemical sensors integrated into SCLs have been of the form of single macroelectrodes; however, microelectrodes (Fig. 1 a,b) have improved sensing properties including faster response, increased sensitivity and limit of detection, and better mass transport [15], [16]. With the limited working area of a SCL, it is also more space efficient to use microelectrodes. The decreased current they generate requires potentiostat chips designed for low-current operation, but current can also be increased by summing the output current of arrays of connected microelectrodes [17] (Fig. 1 c,d). Fabrication of microelectrode discs is well characterized and fabrication on flexible substrates has been demonstrated [18], [19], [20]. Due to their small size, multiple individually-addressable microelectrodes may be incorporated into a single SCL. They may then be functionalized for different biomarkers, leading to multimodal analysis of the tear film, or functionalized for the same biomarker to provide spatial information about, i.e. an "image" or "video" of, the concentration across the surface of the cornea.

An established state-of-the-art SCL platform has been developed at Ghent University [3] under the primary aim of creating an active liquid crystal display. The platform incorporates wireless communication and power, chip integration, biocompatible materials and is thermoformed into a spherical cap shape (Fig. 2 a). Polyimide (PI) and thermoplastic polyurethane (TPU) is cut to shape with tolerance in the region of tens of microns using a laser.

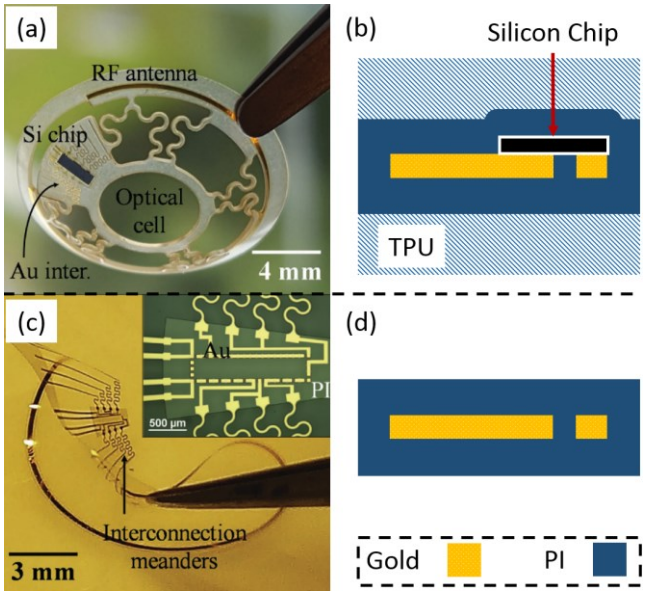

Figure 2. (a) Photograph of thermoformed SCL platform with PI/Au structures and silicon chip embedded in TPU [3]; (b) Schematic side view of the layer structure in *(a)*; (c) Photograph of PI/Au structures before embedding in TPU [3]; (d) Schematic side view of the layer structure in *(c)*.

This method leaves windows which, after embedding in hydrogel (or other soft contact lens material) allows sufficient oxygen permeability for the cornea to remain oxygenated [21].

To ensure compatibility of microelectrodes (or other functionalities) with this SCL platform, similar fabrication methods may be devised and used to create compatible technology. This approach will facilitate integration of multiple sensors, displays and other functions in later devices. The platform consists of metallization layers sandwiched between two PI layers, which is then cut to shape and embedded in TPU for thermoforming (Fig. 2 b). PI is a biocompatible polymer [22], [23] with good chemical resistance and high glass transition temperature [24], which allows for most standard photolithographic cleanroom processes. The position of the metallization between two layers of PI (Fig. 2 c) places it in the neutral mechanical plane (Fig. 2 d), so it is subject to minimal force even while bending. Thus, after embedding this layer stack in TPU and thermoforming into a spherical cap shape, the metallization remains intact. In a microelectrode, the gold layer is no longer in the neutral mechanical plane; it is yet untested how a gold microelectrode fares under thermoforming, but it is expected that smaller electrodes would be better supported and more likely to survive the process than larger exposed areas.

In order to avoid wrinkling of the substrate after forming into a contact lens shape, it is necessary to restrict the circuitry to a narrow defined area [25]. Therefore, the design of sensors and other devices must account for the small available area and the annular shape (Fig. 2 c). A thinned silicon chip is embedded in the platform to carry out signal processing, transmission, and power management. As functionality is added, the demands on this chip increase. Thus, low power consumption and efficient signal conditioning circuitry is crucial for effective integration of additional modalities.

The objective of this work is to use SCL platform-compatible fabrication techniques and materials to make a linear array of individually addressable microelectrodes. The development of this method progresses towards integration of microelectrodes into SCLs, and the results will inform future designs of electrochemical sensors for SCLs.

With this approach we hope to improve the state of the art in electrochemical SCLs, and work towards multimodal devices which can include various functionalities developed by different groups around the world.

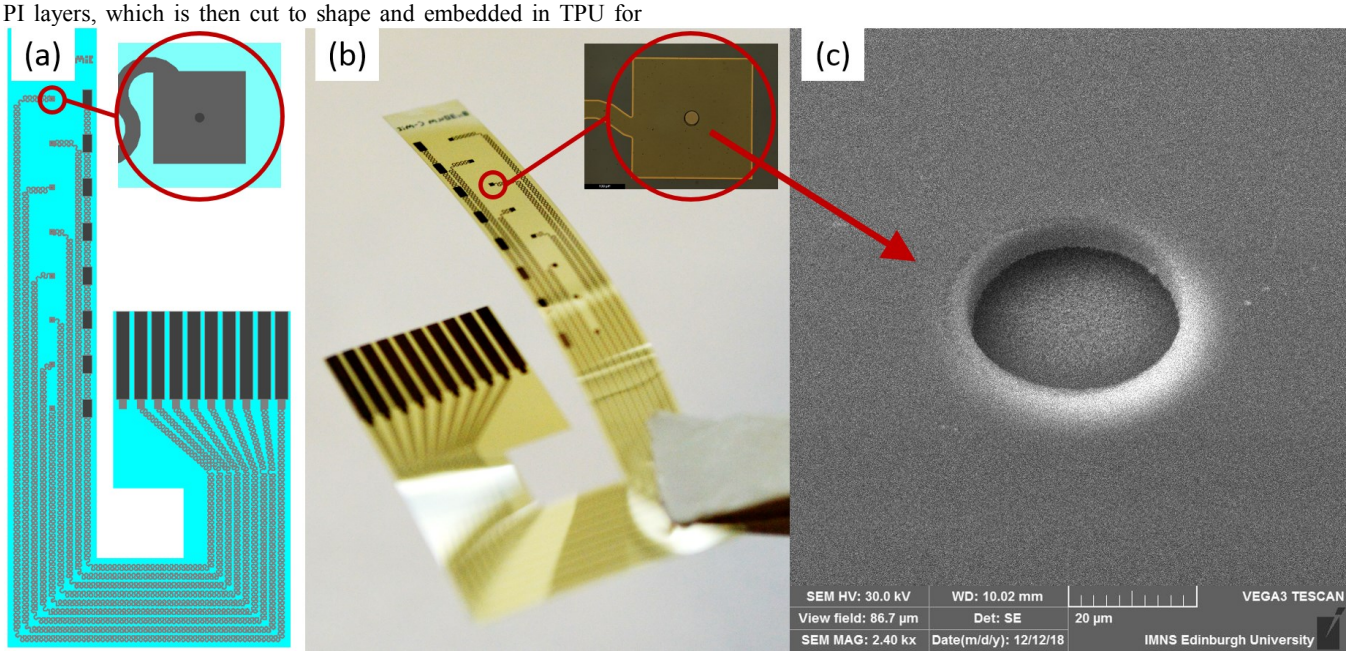

Figure 3. (a) Design of the 8x1 linear electrode array device; (b) photograph of completed device – inset shows photomicrograph detail of a working electrode; (c) SEM image of a gold microelectrode recessed into the PI substrate.

2. Results

An 8x1 linear array of individually addressable microelectrodes was designed, with each microelectrode placed at the same distance from a shared counter electrode site (Fig. 3 a). The working electrodes are discs of 30 µm diameter, recessed 5.5 µm into the top substrate (equal to the thickness of the PI layer) (Fig. 3 c). The metallization layers are gold (60 nm) with an adhesion layer of titanium (40 nm); the device has a total thickness of 11 µm. This device was fabricated using standard cleanroom processes, including photolithography, RIE and wet etching, with no observed damage to the polymer substrates. It is flexible (Fig 3. b) and robust under normal laboratory use.

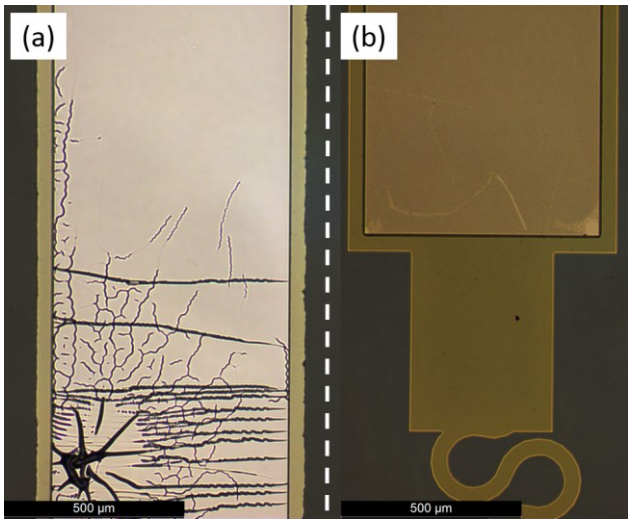

Figure 4. (a) Damaged platinum layer at the (exposed) contact pad. The platinum layer was intact in regions where the top layer of PI was present. (b) Intact gold layer at the contact pad.

No signs of cracking or other damage were observed at the exposed gold sites, either at the small working electrodes, the larger counter electrode or the contact pads. This is in part due to the material properties of the gold; a set of devices were fabricated with platinum metallization (i.e. a harder material), and significant damage was frequently observed at the larger exposed regions after bending the device (Fig. 4 a), including the counter electrodes and contact pads.

Gold meanders were used as interconnects within the device, following a well-characterized design [26], though straight line connections were also tested and proved robust. The devices showed expected electrochemical response in preliminary tests, and individual devices have performed consistently across multiple experiments.

3. Discussion

This device utilizes processes and materials available in the established SCL platform developed at Ghent University to create a flexible array of individually addressable microelectrodes. The same gold layer used for interconnects is used for the sensor structures, and these have proven to be robust even outside of the neutral mechanical plane – an essential characteristic for microelectrodes intended for integration into thermoformed SCL devices.

SCLs have great potential as medical devices, and the development of compatible technologies such as demonstrated here facilitates integration of various functionalities into a single multimodal device in the future. Research is already progressing towards combinations of sensor and display technology [6], and sensor and drug delivery technology [8]. There exists a vast field of unexplored modalities in SCLs and medical devices in general, but there are unique challenges associated both with working within a contact lens and the eye, and the need to share physical space and power resources within the device. Wireless architecture has been demonstrated to safely deliver a power supply on the order of microwatts, or even tens of microwatts [4], though larger power delivery systems may represent too high a cost in terms of antenna size [2]. Similarly, embedded thinned silicon chips have been used in many platforms, but as the number of functions in a SCL increase, the demands on this chip also rise. It is therefore essential to consider efficient use of space, circuitry and power when designing individual functions.

In light of this work there may be exciting possibilities for new combinations of functions – for example, a SCL with microelectrodes and LCD, which could provide active feedback to users or clinicians, or monitor various biomarkers in combination with active vision correction or enhancement.

4. Impact

Our work progresses the field of electrochemical sensors for SCLs in a number of ways. Integration of microelectrodes, with their improved sensing characteristics when compared to macroelectrodes, will lead to more sensitive and accurate sensors. Their size also allows significant parallelization for monitoring multiple biomarkers in one SCL. Further, by developing this technology within the design parameters of an existing SCL platform, the work builds on established research towards clinical use.

5. Acknowledgements

This work was supported by the EPSRC CDT in Integrative Sensing and Measurement, Grant Number EP/L016753/1 in the form of a studentship and additional travel allowance to support the collaborative activity with University of Ghent. The authors would also like to thank Larry & Jane Weber and Larry & Carol Tannas for a student travel grant sponsored by SEL (Semiconductor Energy Laboratory), helping provide the opportunity to present at this conference.

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